RFP-3426
UC-60

# NORTH WIND 2 kW HIGH RELIABILITY WIND SYSTEM

Phase II
Fabrication and Test

June 1982

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Prepared by the

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For

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Energy Systems Group
Rocky Flats Plant
Wind Systems Program
Post Office Box 464
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Subcontract No. PF-71768F

As a part of

United States Department of Energy
Wind Energy Technology Division
Federal Wind Energy Program

DOE Contract No. DE-AC04-76DP03533

WS-44(83)-2:sjb

ABSTRACT

This report describes the Phase II activities (fabrication and testing) performed by the North Wind Power Company, Inc. relative to development of a 2 kW high reliability wind energy conversion system intended for use in remote locations and harsh environments. This program was conducted under Contract No. PF71768F awarded by Rockwell International Energy Systems Group in January 1978 as a part of the United States Department of Energy Federal Wind Energy Program. Phase I activities pertained to system design and analysis and results have been previously published (Reference 1).

Warren Bollmeier was the Rockwell Technical monitor and L. D. Cullen and William Joslyn were Rockwell contract administrators. Clay Waldon was Rockwell's Test Engineer for this project. The final version of the report was extensively edited at Rocky Flats.

North Wind personnel instrumental during Phase II of this project were Donald J. Mayer, John H. Norton, Jr., John Kueffner, Clint Coleman, and Allan Russell.

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## NOMENCLATURE

| | | |
|---|---|---|
| ac | - | alternating current |
| AOM | - | annual operating and maintenance (cost) |
| ASTM | - | American Society for Testing of Materials |
| C | - | centrigrade |
| cc | - | cubic centimeter |
| CDR | - | Critical Design Review |
| cm | - | centimeter |
| $C_s$ | - | Coefficient of System Performance equals that portion of total kinetic energy in the wind available to the rotor capture area which is converted to useable electrical output by the system. |
| $C_p$ | - | Coefficient of Performance equals that portion of the total kinetic energy in the wind available to the rotor capture area which is converted to torque at the main shaft by the rotor. |
| dBA | - | decibels (A-weighted scale) |
| dc | - | direct current |
| $^\circ$ | - | degrees |
| F | - | Fahrenheit |
| FCR | - | Fixed Charged Rate |
| FDR | - | Final Design Review |
| ft | - | feet |
| gm | - | gram |
| Hz | - | hertz |
| HR2™ | - | High Reliability 2 kW - North Wind trade name for the commercial version of the SWECS developed under this contract. |
| IC | - | Installed Cost |
| in | - | inch |

K - Spring constant expressed as a slope in inch pounds of force per degree of torsional deflection.

kg - kilogram

kVA - kilovolt amperes

kW - kilowatt

kWh - kilowatt hours

$\lambda$ - failure rate expressed as number of failures per million hours.

lb - pound

Lundel Rotor - Also known as interdigitated rotor where field coil is wound around central core post with individual field poles wrapped around the outside.

m - meter

$m^2$ - square meter

mm - millimeter

mph - miles per hour

MTBF - Mean Time Between Failure expressed in years.

N-m - newton meter

NWPCo - North Wind Power Company

% - percent

± - plus or minus

PDR - Preliminary Design Review

Ø - phase

r/R - variation (r) from blade chord line at nondimensional radial station (R) of blade.

REA - Rural Electrification Administration

RFP - Request for Proposals (when used in text)

rpm - revolutions per minute

SWECS - Small Wind Energy Conversion System

| | |
|---|---|
| t | - one year |
| v | - volt |
| VARCS™ | - Variable Axis Rotor Control System - North Wind Trade name for the HR2 control system. |
| V | - annual average (mean) wind speed |

# 1.0 INTRODUCTION

In January 1978, the North Wind Power Company, Inc. was awarded a contract to design, fabricate and test a 2 kW wind system capable of unattended operation at remote sites and under severe environmental conditions. The contract was sponsored by the U.S. Department of Energy and administered by Rockwell International Corporation as part of an effort to expedite the use of small (under 100 kW) wind systems. Contract activities were divided into two phases: 1) system design and analysis; and 2) prototype fabrication and testing.

After contract initiation North Wind proceeded with the design of a high reliability wind system that would produce 2.2 kW of power at wind speeds of 9 m/s (20 mph). During Phase I of the program, a predecessor of the proposed design was procured and tested in a wind tunnel and in the free stream to observe operational characteristics (see Reference 1). An analytical procedure was developed for designing and modeling the proposed variable axis rotor control system (VARCS™). This procedure was then verified by extensive testing of preprototype components. A low-speed, three-phase alternator with a Lundel type rotor was also approved for Phase II prototype fabrication and testing.

This report presents the results of Phase II of the program in which three (3) production prototypes were fabricated and tested. It also contains descriptions of some design and analysis activities which continued into Phase II. Prototype #1 was tested at North Wind Power Company's facilities for one and one-half months prior to shipment to Rocky Flats. Testing at Rocky Flats continued until a bent shaft was discovered, at which time unit #1 was replaced with prototype #2. Testing of #2 (Figure 1) is ongoing at Rocky Flats and results will be published at a later date. Since the start of unit #2 testing, a third prototype has been installed at North Wind for parallel testing. Upon completion of the in-house test program, this unit will be shipped to Rocky Flats. A contractor organizational chart and Phase II schedule are shown in Tables I and II, respectively. Phase II activities were completed during December 1980.

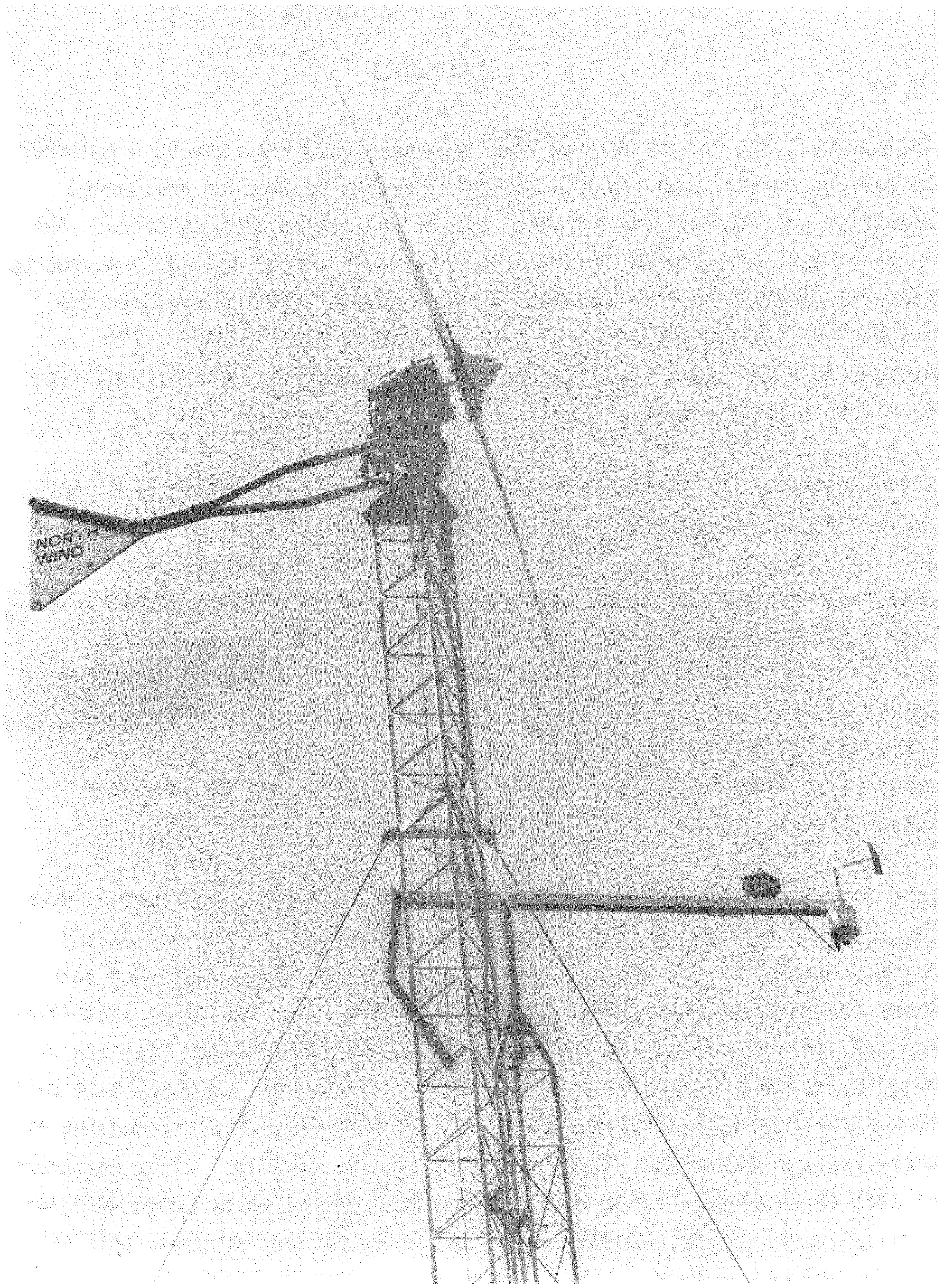



Figure 1
North Wind 2 kW High Reliability Prototype

TABLE I

North Wind Power Company
Phase II Organizational Chart

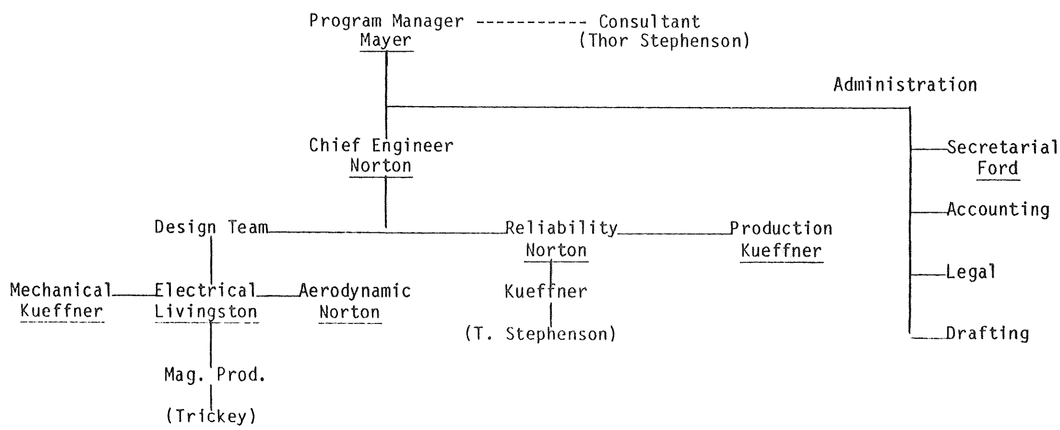
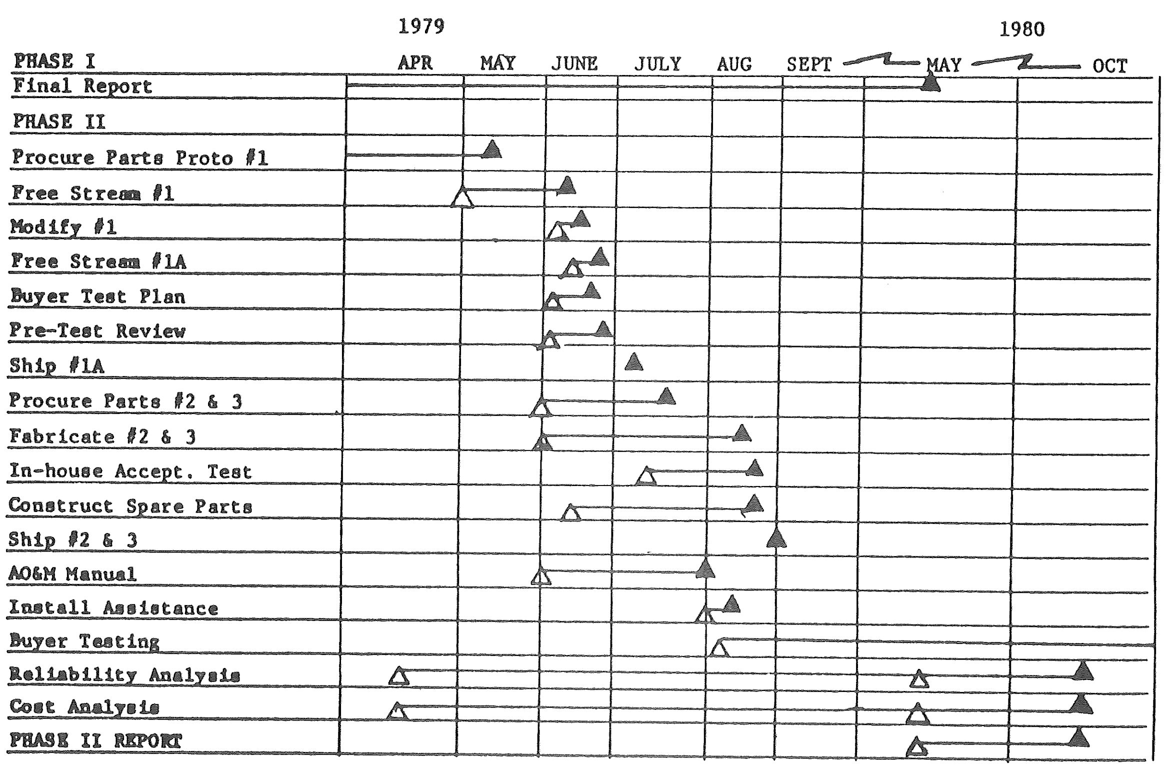



TABLE II

Phase II Schedule



## 2.0 DESIGN OVERVIEW - NORTH WIND HIGH RELIABILITY 2 kW SWECS (HR2)

The design philosophy of North Wind Power Company was to base the development of this small wind system on older concepts which the company has been able to refine and augment by using analytical modeling techniques and advanced materials. Design concepts such as a three-bladed upwind rotor, a direct-drive electrical generator, and the Parris-Dunn method of speed control by rotor tilt-back were applied to the HR2. North Wind Power Company's objective for this program was to develop a design emphasizing simplicity, durability, and cost-effectiveness without degrading performance or reliability. The direct-drive generator and variable axis rotor control system (VARCS) were selected to meet this design objective. Figure 2 is a schematic of the overall configuration of the HR2.

The VARCS was selected to be the cornerstone of the HR2's system reliability. The rotor tilt-back design reduces the complexity and expense associated with a variable pitch hub assembly requiring an additional folding tail or shutdown/reorientation device for protection in extreme winds. Figure 3 is a schematic of VARCS operation. A direct-drive, low-speed generator was developed to meet the program's cost and performance goals by eliminating the need for a high-speed generator employing a gear box. Use of these components minimizes the number of moving parts in the HR2, thereby contributing to increase reliability and minimize maintenance.

The HR2 is designed to produce 2200 watts of electric power at wind speeds of 9 m/s (20 mph) and maintain a 700 watt continuous load at a site with average winds of 5.4 m/s (12 mph). Table III lists the prototype's final system specifications.

<u>Contract Design Specifications (Untested):</u>

- Mean time between failures: calculated at 131,000 hours.
- Maintenance: less than one man day per year.
- Design life: 25 years.
- Operating costs: less than 1% of the installed cost.
- Operating temperature range: -70°C to 60°C (-94°F to 140°F).
- High wind survival speed: 74 m/s (165 mph).
- Environmentally sealed and corrosion protected.

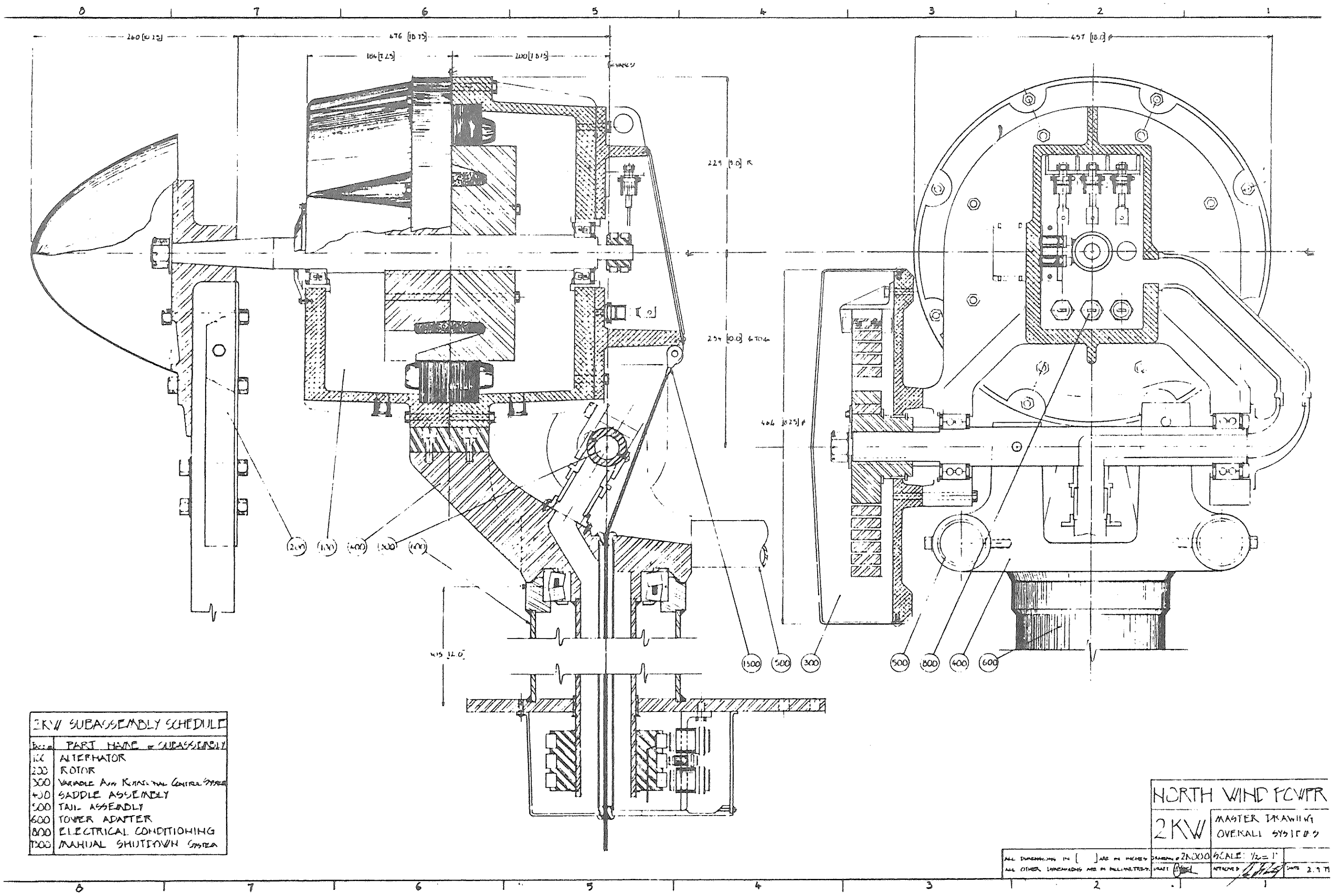
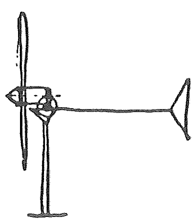



Figure 2

North Wind HR System Schematic

Figure 3

Variable Axis Rotor Control System (VARCS)
Operational Modes



1. STANDARD OPERATIONAL MODE

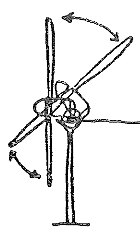
   $5^{\circ}$ TILT AT START-UP TO ACCOUNT FOR BLADE DEFLECTION

   CUT-IN WIND SPEED: 10MPH

   MAX WIND SPEED THIS MODE: 21MPH

   MAX POWER OUTPUT THIS MODE: 2203WATTS

   MAX RPM THIS MODE: 250RPM

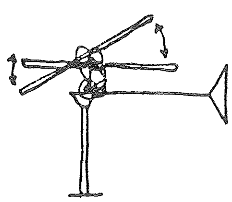


2. AXIS ROTATION VERTICALLY

   OVERSPEED CONTROL

   CONTROL INITIATION: 21MPH

   SHUTDOWN: 105MPH

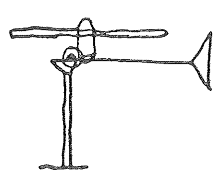


3. SHUT DOWN --- 105MPH

   AXIS ROTATION TO $90^{\circ}$

   POWER AND RPM'S APPROACH 0

   SPRING TENSION REALIGNS ROTOR AS GUSTS SUBSIDE



4. MANUAL SHUT DOWN

   SERVICE AND MAINTENANCE

TABLE III

NORTH WIND 2 kW HIGH RELIABILITY
SYSTEM SPECIFICATIONS

| | |
|---|---|
| General Description | 3-bladed, horizontal axis, upwind |
| **Physical Description** | |
| Weight (less tower) | 356 kg (785 lb) |
| Rotor Diameter | 5 m (16.4 ft) |
| Tower Height | 12.2 m (40 ft) |
| **Operational Characteristics** | |
| Cut-in Wind Speed | 3.6 m/s (8 mph) |
| Speed Control Initiation | 9.4 m/s (21 mph) |
| System Shutdown | 47 m/s (105 mph) |
| Survival Wind Speed | 73.7 m/s (165 mph) |
| Rated Output @ Wind Speed | 2.2 kW @ 9.3 m/s (21 mph) |
| Rotational Speed @ Rated Output | 250 rpm @ 2.2 kW |
| $C_s$ @ Rated Output | .29 |
| Yearly Output in V = 5.36 m/s (12 mph) | 6,000 kWhrs |
| = 6.70 m/s (15 mph) | 7,800 kWhrs |
| = 7.15 m/s (16 mph) | 8,400 kWhrs |
| = 8.04 m/s (18 mph) | 9,600 kWhrs |
| **Rotor** | |
| Weight (Blades, Hub) | 41 kg (90 lb) |
| Diameter | 5 m (16.4 ft) |
| Capture Area | 19.63 $m^2$ (2.11.2 $ft^2$) |
| Solidity | .04 |
| Tip Speed Ratio | 7.5 |
| $C_p$ at Rated Output | .41 |
| **Blades** | |
| Material | Sitka spruce (aircraft grade) |
| Planform | Linear taper from 200 mm (8") @ r/R = .3 to 80 mm (3.1") @ tip |
| Twist | Non-linear from 12.5° @ r/R = .3 to .5° @ tip |
| Airfoil | G625 from r/R = .1 to r/R .3, N60 from r/R = .3 to tip (modified) |
| **Hub** | |
| Material | Cast and wrought steel (ASTM 148-73 Class 80-50) |
| Type | Fixed Pitch |

TABLE III (Continued)

| | |
|---|---|
| Generator | |
| Type | 3 Ø synchronous alternator (Lundel rotor) |
| Nominal Voltage | 24 vdc |
| Size | 458 mm (18") by 368 mm (14.5") |
| Number of Poles | 12 |
| Synchronous Speed @ 25 Hz | 250 rpm |
| Rated Power @ Speed | 2.2 kW @ 250 rpm |
| Efficiency | 70% @ rated speed and output |
| Weight | 133 kg (295 lb) |
| Speed Control | |
| Type | Variable Axis Rotor Control System (VARCS) |
| Spring | Spiral Torsion Spring K = 71 in. lbs/degree |
| Rotor Tilt Range | 10° to 90° (from horizontal to vertical) |
| Yaw Control | Free yawing |
| Tower | |
| Type | Unarco Rohn 45 GSR double guyed |
| Material | Galvanized steel |
| Height | 12.2 m (40 ft) |
| Weight | 700 kg (1555 lb) |
| System Cost (1000th unit) | |
| Unit | \$2867 |
| Tower | 700 |
| Storage | 2000 (24 volt/800 amp hour) |
| Installation | 1200 (site dependent) |
| TOTAL | \$6767 |
| Cost of Energy | |
| Installed Cost | \$6767 |
| Fixed Charge Rate | .085 |
| Annual Operations & Maintenance Cost | \$135 |
| Annual Kilowatt Hours Produced | 10,981 (assume 6.7 m/s [15 mph] average) |

$$COE = \frac{IC\ (FCR) + AOM}{kWhrs}$$

$$COE = \frac{6767\ (.085) + 135}{7800}$$

COE = \$.091 per kilowatt hour

## 3.0 DESIGN CHANGES RESULTING FROM ANALYSIS

### 3.1 HR2 Alternator Design Changes

Analysis and in-house component testing resulted in several design changes to the HR2 alternator during Phase II.

In-house component testing indicated that additional magnetic material was needed in the Lundel rotor to improve the residual magnetism and, hence, self-excitation characteristics. Magnetic material was subsequently added in the form of a 6" diameter 1/4" thick hardened steel disc. Later, a hardened tool steel washer was added in the alternator rotor between the two halves of the Lundel to further improve self-excitation. The alternator modifications detailed (in sequence) in Table IV reduced self-excitation rpm from 250 to below 200.

TABLE IV

PHASE II ALTERNATOR MODIFICATIONS

| DESIGNATION | | DIA. @ AIRGAP | STATOR WINDING | ROTOR WINDING |
|---|---|---|---|---|
| 3B | 0.625 01 tool steel magnetic washer | 15.375 | 9 T, 4 in hand #13 | 858 T #17 |
| 3C | Two .0625 01 washers | 15.375 | 9 T, 4 in hand #13 | 858 T #17 |
| 3D | .125 A2 tool steel magnetic washer | 15.375 | 9 T, 4 in hand #13 | 858 T #17 |
| 4 | .125 A2 tool steel magnetic washer | 15.375 | 11 T, 4 in hand #14 | 540 T #14 |

### 3.2 Other Design Changes Resulting from Analysis

A power conduit connector was replaced with a flexible cast silicon boot between the VARCS shaft and saddle to improve and simplify tower installation and reduce unit cost.

The spring hub and shaft design was simplified to improve manufacturability. This change reduced the sub-assembly parts count from six (6) to two (2) and lowered manufacturing costs by eliminating a redundant bearing assembly.

The VARCS spring length was shortened to increase the spring rate to 71 in lb/degrees. The modification was based on test data which dictated a revision of the computer model. Redesign with the revised model indicated a stiffer spring was required to match the desired power curve and raise the peak output from 1500 watts to 2200 watts at a wind speed of 9 m/s (20 mph).

Tail arms were lengthened by 1" to generate greater yaw movement, thus providing greater yaw stability with respect to the precessional forces generated during tilt-back and tilt-down.

## 4.0 FABRICATION AND ASSEMBLY OF HR2 PROTOTYPES

In the construction of the HR2 prototypes, all major components, with the exception of the rotor blades, were manufactured and machined out-of-house. These included rotor hub and shaft; alternator and castings; saddle mount; VARCS springs; plates and discs; endbells; tower top; and tail-vane. At the North Wind facilities, only assembly work, miscellaneous parts fabrication, and component testing were carried out.

### Rotor

The rotor blade fabrication process was accomplished by employing the blade fabrication techniques which North Wind had previously developed for the North Wind Eagle (Reference 2). Each three-blade set for the prototype models began with rough-cut Sitka spruce blades fabricated from 2"x8"x98" stock by a vendor using hand carving techniques. The rough blades were inspected to assure proper chord angle within 1/2° of the specifications. Using an in-house-developed angle cutting machine, which utilizes a belt sander and a molded blade-support platform, each blade was ground to the correct chord angle and given an acceptable surface finish.

The roots of the blades were then drilled for all rotor hub attachment points. The leading and trailing edges of each blade were inspected with templates to determine the extent to which the blade required final finish sanding in order to achieve the correct airfoil sections with consistent precision. The first coat of one part polyurethane with paint was applied and then the self-adhering leading edge protective tape fitted to the blade. Each blade was finished with two more coats of paint. As the final step in producing a complete HR2 blade set, the blades were balanced by means of a gravity moment measuring device, using the heaviest blade as the reference (see Figure 4). Where necessary, lead weights were attached with brass screws at the root of the blades to achieve a matched and balanced blade set. The specific balancing modifications to each set were recorded and catalogued.

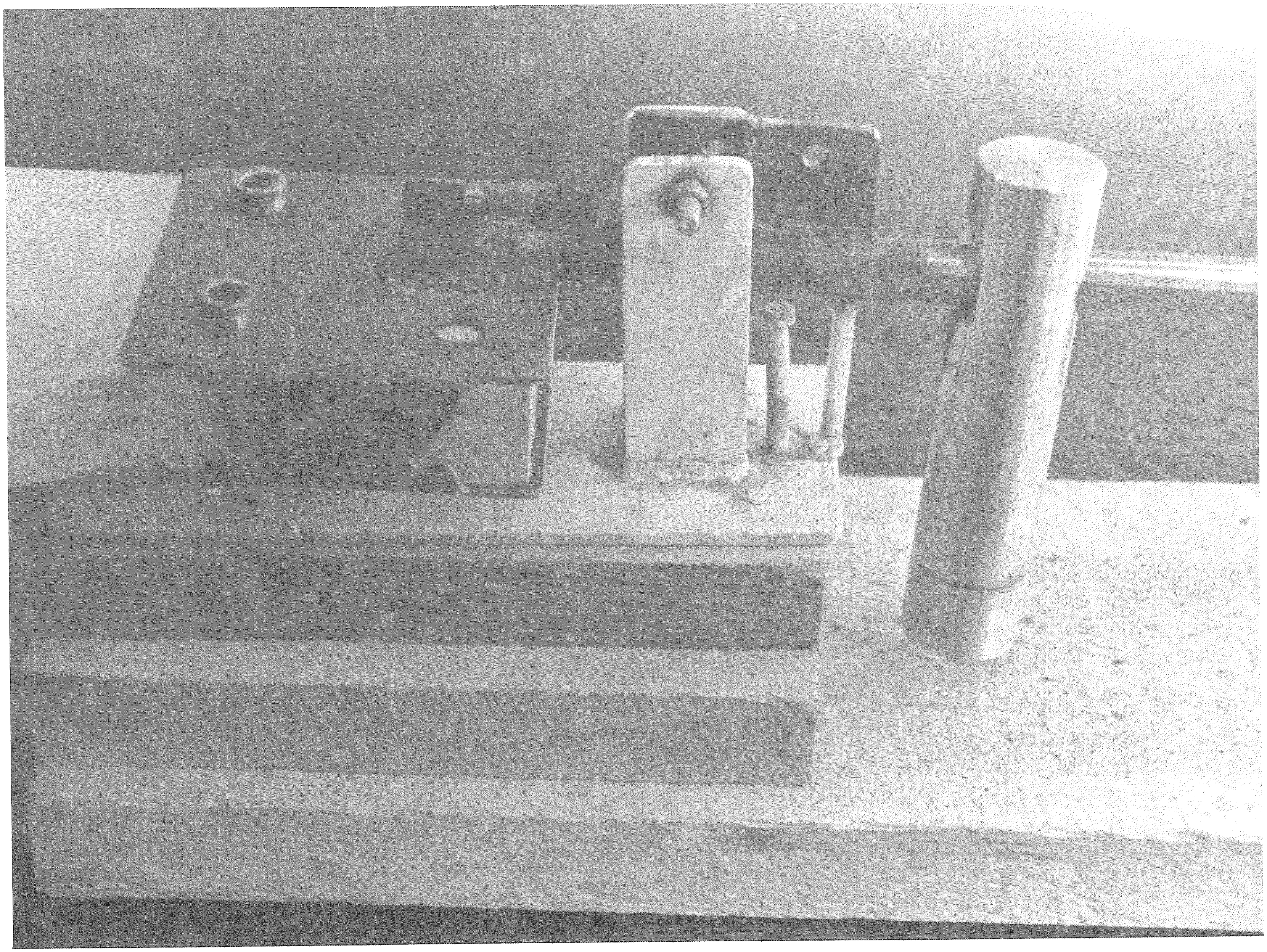


Figure 4
Balancing of HR2 Blades

The two-part rotor hub (casting and pressure plate) was then fitted with all three blades to assure proper overall rotor balance. The entire fabrication and assembly check-out required two skilled workers 48 man-hours per rotor.

## VARCS

The VARCS spring was manufactured by an outside vendor from a 144" long 1/2" by 1 1/2" bar of 4140 steel. The bar was heated and coiled into a spiral approximately 13" in diameter with a 3/8" space between each coil. The completed coil was then annealed and shipped to North Wind.

In the completed VARCS assembly (Figure 5), the spring was clamped into the VARCS hub at the inside coil and mounted on the VARCS shaft. At the outer radius, the spring was attached by a bracket to the VARCS disc mounted on the alternator assembly. A bar bolted to the VARCS disc and bearing on the inactive excess portion of the spring acted as a bridle to maintain the concentricity of the spring as the machine pitched back. This bar also acted as a 90° positive stop.

## Alternator

Alternator assembly consisted of setting the pre-stacked and wound stator in the rear endbell and dressing out the power leads for connection to the rectifiers, then assembling the rotor. Rotor assembly involved pressing the front Lundel casting on the shaft, fitting the completed field coil around the Lundel core and bolting the rear Lundel casting to the front casting.

The rotor coil leads were dressed out along the shaft and the front and rear bearings pressed on. The entire assembly was completed when the finished rotor was lowered into the rear endbell and stator, the front endbell bolted on and all connections to the rectifiers and slip rings completed (see Figure 6). This finished assembly was then tested on the dynamometer for final acceptance. Results are presented in Table V.

TABLE V

Contractor Dynamometer Test Results.

| Load Setting | Field Current ($I_2$) | Field Voltage ($E_2$) | Input Torque (N-M) | RPM | Input Power = .105 O*RPM | Output Current ($I_1$) | Output Voltage ($E_1$) | Output Watts ($W_2$) | Eff ($P_2$) |
|---|---|---|---|---|---|---|---|---|---|
| - | 14.3 | 52 | | 250 | | | 52 | | |
| 0 | 13.7 | 50 | | | | 5 | 50 | | |
| 25 | 12.5 | 48 | 80 | | 2100 | 24 | 48 | 1152 | 55 |
| 50 | 11 | 42 | 136 | | 3570 | 50 | 42 | 2100 | 59 |
| 75 | 10 | 40 | 159 | | 4174 | 62 | 40 | 2480 | 59 |
| 80 | 10 | 39 | 160 | | 4200 | 64 | 39 | 2496 | 59 |
| 85 | 9.6 | 38.5 | 143 | | 3754 | 67 | 38.5 | 2580 | 69 |
| 90 | 9.5 | 38 | 138 | | 3623 | 69 | 38 | 2622 | 72 |
| 95 | 9.3 | 37 | 140 | | 3625 | 72 | 37 | 2664 | 72 |
| 100 | 8.8 | 35.4 | 146 | | 3833 | 78 | 35.4 | 2761 | 72 |
| 110 | 8.6 | 34.6 | 147 | | 3859 | 80 | 34.6 | 2768 | 72 |
| 120 | 8.3 | 33.5 | 150 | | 3938 | 83 | 33.5 | 2781 | 71 |
| 130 | 8 | 32.4 | 150 | | 3938 | 86 | 32.4 | 2786 | 71 |
| 140 | 7.7 | 31 | 150 | | 3938 | 89 | 31 | 2759 | 70 |
| 150 | 7 | 28.5 | 144 | | 3780 | 93 | 28.5 | 2651 | 70 |
| 160 | 6.9 | 28 | 139 | | 3649 | 94 | 28 | 2632 | 72 |
| 170 | 6.6 | 26.7 | 136 | | 3570 | 94 | 26.7 | 2510 | 70 |
| 180 | 6.2 | 25 | 131 | | 3439 | 94 | 25 | 2350 | 68 |
| 190 | 5.9 | 23.9 | 124 | | | 93 | 23.9 | 2223 | |
| 200 | 4.9 | 19.6 | 91 | | | 83 | 19.6 | 1627 | |
| 210 | 4.3 | 17.8 | 82 | | | 78 | 17.8 | 1388 | |
| 220 | | | | Collapsed | | | | | |
| 150 | 8 | 32 | 165 | 275 | 4764 | 104 | 32 | 3328 | 70 |
| 125 | 8 | 32 | 146 | 250 | 3833 | 85 | 32 | 2720 | 71 |
| 100 | 7.7 | 32 | 127 | 225 | 3000 | 69 | 32 | 2208 | 74 |
| 60 | 7.8 | 32 | 92 | 200 | 1932 | 40 | 32 | 1280 | 66 |
| 25 | 7.8 | 32 | 44 | 175 | 808 | 16 | 32 | 512 | 63 |
| 10 | 6.7 | 27.5 | 24 | 150 | 378 | 5 | 27.5 | 138 | 36 |

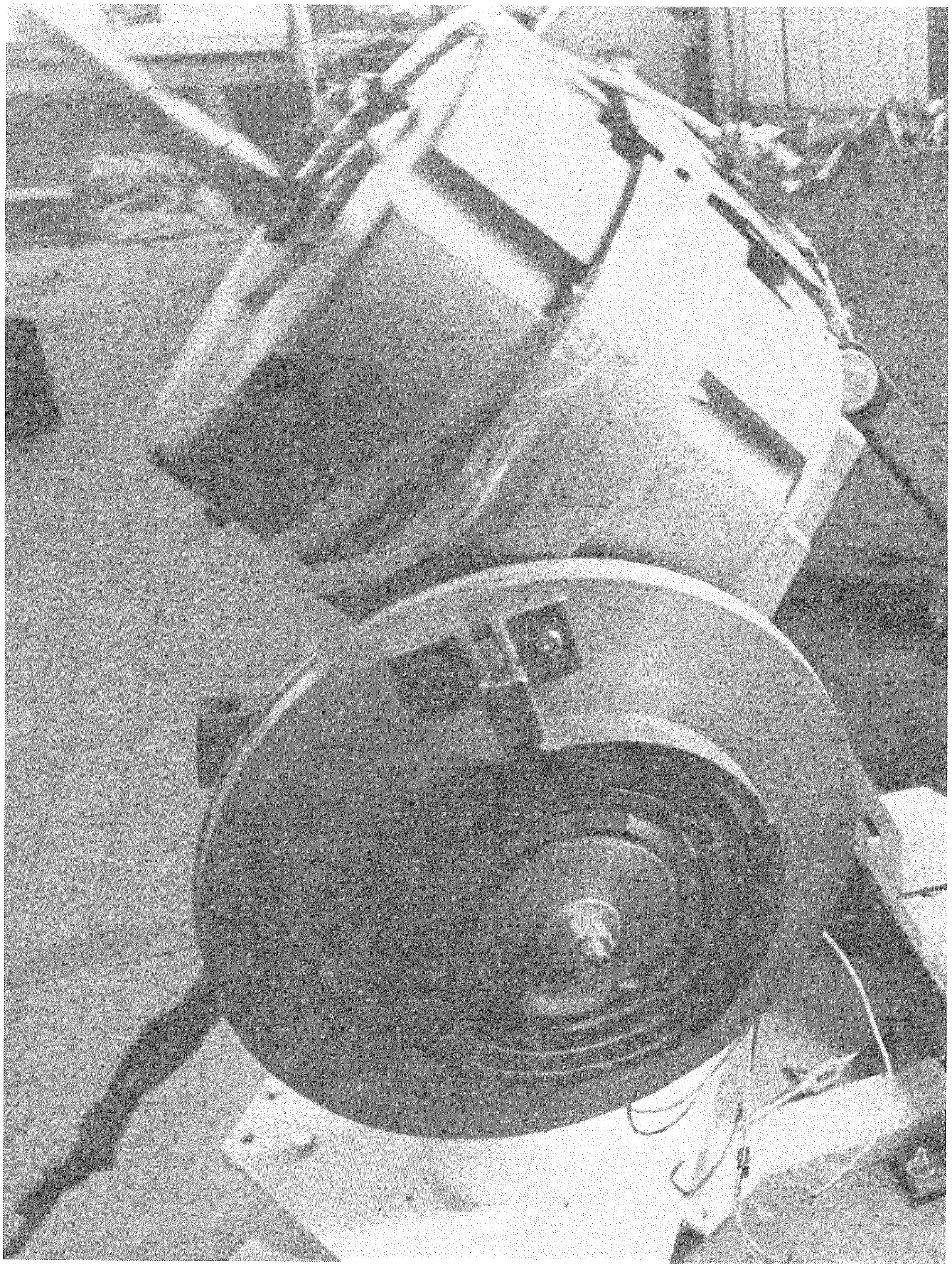


Figure 5
Completed VARCS Assembly

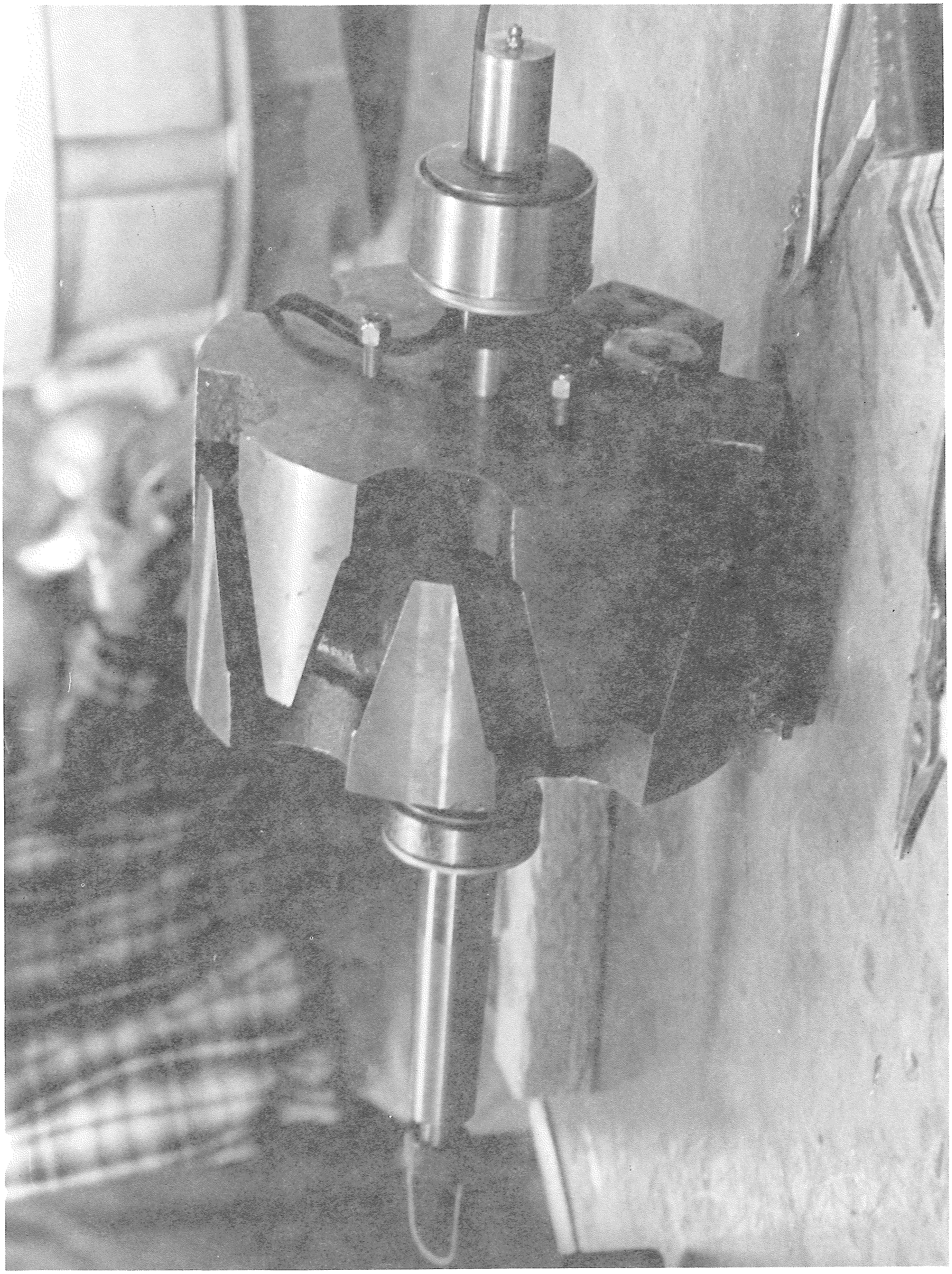


Figure 6
Completed HR2 Alternator

## Quality Assurance

Quality control during Phase II prototype fabrication and assembly procedures was maintained by the Production Manager at North Wind Power Company. Key dimensions of all components and specific tolerances were monitored and maintained. Acceptance criteria were developed for all critical subassemblies and test procedures carried out to verify compliance. A sample of acceptance criteria is shown in Figure 7.

BOWSTEEL CORP.

P. O. BOX 164
LINDEN, N. J.
07036

P. O. BOX 8716
GREENVILLE, S. C.
29604

P. O. BOX 459
WINDSOR, CONN.
06095

3700 BLVD. ST. JOSEPH. E
MONTREAL, QUE. CANADA
H1X 1W6

North Wind Power
Box # 315
Warren, Vermont 05674

Cold Drawn Annealed
Aircraft Quality Steel
Vacuum Degassed

| YOUR ORDER NO. | WEIGHT | SIZE | GRADE |
|---|---|---|---|
| 3693 | | 1/2" x 1-1/2" Rect. | 4340 |

CHEMICAL ANALYSIS

| MILL | HEAT NO. | C | MN | PHOS | SUL | SIL | NI | CR | MO | AL | CU | | AMS 2301 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Republic | 8080842 | .41 | .74 | .005 | .013 | .24 | 1.69 | .78 | .28 | | .17 | | F .06<br>S .06 |

PHYSICAL PROPERTIES

| TENSILE STRENGTH LBS./SQ. IN. | YIELD LBS./SQ. IN. | ELONG % IN IN. | RED. OF AREA % | BRINELL | ROCKWELL "C" | G/S | DECARB | HARDENABILITY JOMINY | HARDENABILITY BRINELL |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 255 | ~25 | 5/8 | .012mx | 6 20·32<br>57 55 52 | |

MACRO REQUIREMENTS MEET SPEC MIL-STD-430 and ASTM-E381 (S2, R1, C2)

Sworn to and subscribed before me

This 27th Day of August 1980

Peter L. Civory

NOTARY PUBLIC OF Connecticut
MY COMMISSION EXPIRES
NOTARY PUBLIC
My Commission Expires March 31, 1983

I CERTIFY THAT THIS IS A TRUE COPY OF ORIGINAL TEST SHEET NOW ON FILE AT THE OFFICE OF THE BOWSTEEL CORPORATION.

BY [signature]
General Manager

Figure 7

Example of Acceptance Criteria

## 5.0 DESIGN CHANGES AND CONTRACTOR TESTING OF PROTOTYPE #1

Prior to shipment to Rocky Flats, North Wind tested Prototype #1 on its truck test facility and on a tower at its Warren facility. Prototype #1 was instrumented for the following operational parameters: current, voltage, power output, rpm, wind speed, pitch, yaw and wind direction. Data were reduced from all these parameters both as instantaneous values and as averages by using the digitizing program on the "Arga Wind Tape" (Reference 1). Data obtained from current, rpm, and wind speed curves were calculated and averaged. For calculation of average power, the voltages were averaged over the period and multiplied by the average current (Figure 8).

Values obtained by these methods fell within a narrow band up to control velocity and tracked well the theoretical calculations (Figure 9). This wide divergence after tilt-back was confirmed in testing at Rocky Flats and was assumed to be due to control hystersis.

Contractor testing continued from mid-July to mid-August 1979. During this period the machine operated while connected to a battery bank. Wind speeds as high as 26 m/s (60 mph) were recorded during thunderstorms. During one such storm, a blade was broken when it deflected into the tower. This failure was attributed to a particularly soft (light-weight) blade and insufficient pre-pitch of the rotor to provide adequate tower clearance. Consequently, blade tests were performed resulting in an increase in pre-pitch from 5° to 10°. Blade specifications for weight were increased to assure sufficient material density and, hence, strength. Procedures and test results of the blade deflection tests are shown in Table VI. The modified material and fabrication specifications are shown in Table VII.

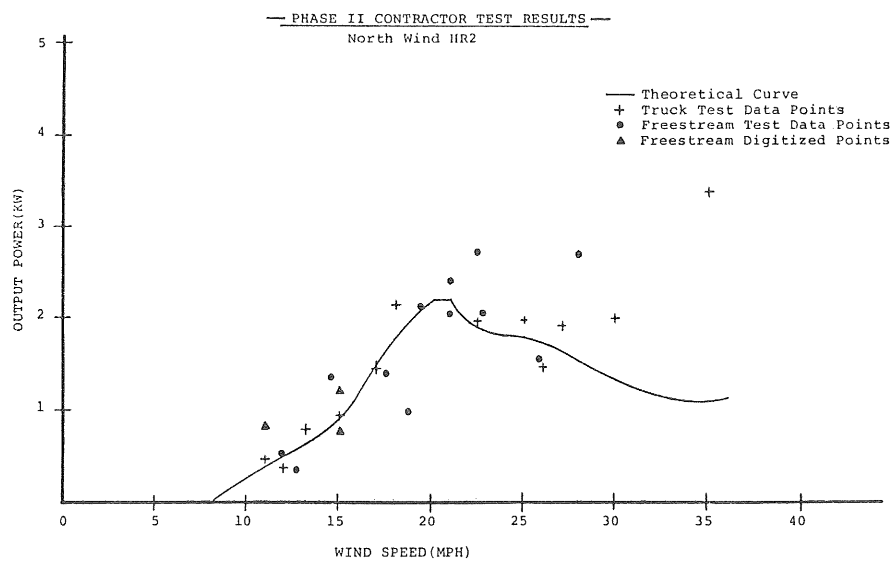



Figure 8

Contractor Power Curve

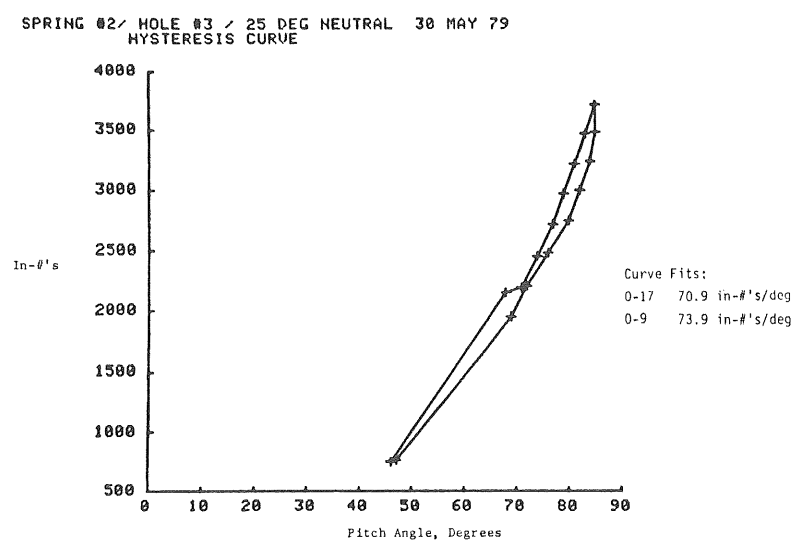



Figure 9

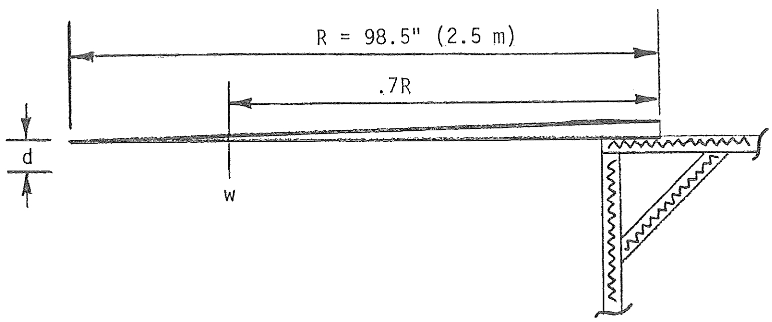
Contractor Hysteresis Curve

TABLE VI

BLADE DEFLECTION TESTS

Procedure:

Each test blade was bolted to the rotor hub casting and pressure plate, which were, in turn, clamped and bolted to a workbench top, upwind side of the blade facing up. Test weights were applied at the .7R point (69"/1.75m) and blade deflections were measured at the tip, as diagrammed below:




Results:

| Blade | Description | Weight | Weight, w(lbs) | Deflection (in) |
|---|---|---|---|---|
| 5m, N60#7 | Finished Painted | 9# 11-1/4oz. | 94 | 12.75 |
| 5m, N60#7 (broken) | Finished Painted w/inlaid lead | 7# 6-1/2oz. | 94 | 19.25 |
| 5m, N60#8 | "J", finished bare | 6# 15-1/4oz. | 94 | 16. |
| 5m, N60#8 | "M", raw full root | 9# 6-1/4oz. | 94 | 12.5 |
| 5m, N60#8 | "M", finished painted | 8# 7-1/4oz. | 94 | 13.875 |

## TABLE VII

## BLADE MATERIAL AND FABRICATION SPECIFICATIONS

### Blade Material Specifications

Wood for blade to be "Sitka spruce," "select structural," maximum moisture content of 19% and specific gravity of 0.4, ±0.01.

Wood shall be selected with minimum defects, for 12" length at rotor shaft end. No defects, including knots, checks, etc., shall be permitted at connections or upwind of the quarter chord over blade length.

Wood shall be straight-grained, with fibers parallel to the length of the blade.

### Blade Fabrication Specifications and Tolerances

| | |
|---|---|
| Weight | 9 pounds, plus or minus 8 ounces (see material specifications above) |
| Butt Width | 5 15/16", plus or minus 1/16" |
| Butt Thickness | 7/8", plus or minus 1/64" |
| Station Twist Angle | Template, plus or minus 1/2° (measured on upwind surface) |
| Station Chord Length | Template, plus or minus 1/16" |
| Bend-over Length | Plus or minus 1/4" (measured to reference, using upwind surface as base) |

## 6.0 DESIGN CHANGES TO PROTOTYPE #2

The most important design change made to prototype #2 was a result of test experience obtained at Rocky Flats with the discovery that the main shaft of prototype #1 was bent directly behind the hub casting. This bend occurred along the axis of one of the three blades. Although no wind load could be identified as the cause, calculations of the shaft section properties at that point revealed that sufficient force to bend the shaft could be applied by service personnel at the blade tip during installation or maintenance.

Following this development at Rocky Flats, North Wind Power Company redesigned the shaft taper at the hub to provide approximately 40% additional section. The shaft material was respecified from AISI 1141 to AISI 4340, hardened to RC 35. This new shaft was retrofitted to Prototypes #2 and #3.

Due to preliminary results from Rocky Flats, which indicated an instability in torsion at the upper limit of the operating range (400 rpm), the blades of prototypes #2 and #3 were also redesigned for additional structure. The new blade design provided 15% additional section at the quarter chord, resulting in a 25% increase in factor of safety. Both shaft and blade redesign were based on the performance and reliability criteria discussed in Section 8.0. The phenomenon was later determined to be due to the bent shaft discussed above, rather than instability. Prototype #2 is currently undergoing testing at Rocky Flats.

## 7.0 DESIGN CHANGES AND CONTRACTOR TESTING OF PROTOTYPE #3

In November 1979, the third prototype was installed at North Wind Power Company. Initially, high noise levels were recorded as rpm approached 400 and assumed to be due to the soft blade deflecting torsionally at high rpm. Shortly after this observation, a redesigned set of blades was put into operation which met the specifications developed on the basis of the

Rocky Flats test experience, and no excessive noise levels were recorded. This system operated with no difficulty in a "no load" configuration until March 1980. However, in late March during a storm with gusts to 17.9 m/s (40 mph), all three blades were broken. Examinations revealed the cause of this failure to be blade impact with the tail vane. The ninety degree stop (actually found to be 93°) had maintained only 2" of clearance, which was insufficient for protection from high gust-induced pitch rates. This, and all stops, were then modified to 88° to provide 12" of clearance in the pitch-back mode of operation.

There have been little performance data collected in the company's free-stream testing of prototype #3. The main objective of the free-stream testing is to acquire operational hours on the prototype, while the acquisition of additional empirical data is left to Rocky Flats.

## 8.0 SUMMARY OF PHASE II DESIGN CHANGES AND PROTOTYPE MODIFICATIONS

There were four criteria which governed all design change decisions made on the HR2 prior to and during prototype construction. Each design change or modification made to the prototypes was evaluated and implemented for its potential to improve 1) manufacturability (reduce costs, simplify construction); 2) reliability (increase part rating or reduce parts count); 3) maintainability (considering a remote site location); and 4) performance, (increase system efficiency and output or reduce wear and stress).

In addition to the blade, shaft and VARCS tilt-back modifications (described previously), there have been numerous small changes to HR2 drawings. These drawings are presently in the possession of Rocky Flats and changes are listed in Appendix A. None of the Phase I analyses of reliability cost and energy output were significantly altered by Phase II modifications.

Table VIII indicates the overall scope of Phase II design changes; however, many simple mechanical drawing updates or corrections are not listed.

TABLE VIII

Significant Phase II Design Changes

| SUBSYSTEM | PART NAME | PART NO. | DESCRIPTION OF CHANGE | REASON |
|---|---|---|---|---|
| Alternator | Field Rotor | 2k120 | Added .125" hardened steel washer between Lundel castings to provide higher residual field magnetism. | Performance - lowered self-excitation rpm from 250 to 175. |
| Rotor | Blades | 2k210 | Moved airfoil transition section outboard airfoil selection from 12% to 14% to stiffen blade. | Reliability - provided additional out-of-plane strength and torsional stiffness. |
| Drive Train | Main Shaft | | Redesigned shaft taper at hub to give 40% additional section. Re-specified shaft material to AISI 4340, hardened to RC 35. | Reliability - strengthened shaft to prevent bending from loading at blade tip. |
| VARCS | 90° stop assembly | -- | Add assembly to the VARCS mechanism consisting of arm attached to hub and stop bracket attached to disc to provide positive stop for 88° tilt-back. | Performance - prevented over-pitch and consequential intersection of tail with plane of turbine rotation. |
| | Power Conduit | -- | Replace connector with flexible cast silicon boot between VARCS shaft and saddle. | Manufacturability and Maintenance - reduced unit cost by approximately $200 and simplified installation procedure. |
| | Spring Hub & Shaft | -- | Simplify Design | Manufacturability |
| | VARCS Spring | -- | Shorten spring length to increase spring rate to 71 in lb/deg. | Performance - improved maximum output from 1.5 kW to 2 kW. |
| Tail | Tail Arms | -- | Lengthen tail arms to provide more yaw stability. | Performance - improved yaw stability during tilt-back and tilt-down. |

## 9.0 UPDATED COSTS/ECONOMIC PROJECTION

### 1. Prototype Costs

| Code | Sub Assembly | Cost of 1st Unit |
|---|---|---|
| 100 | Alternator | $2100 |
| 200 | Rotor | 700 |
| 300 | VARCS | 1170 |
| 400 | Saddle | 894 |
| 500 | Tail | 53 |
| 600 | Stub Tower | 525 |
| 800 | Electrical Conditioning | 84 |
| 900 | Electrical Regulation | 300 |
| 1300 | Manual Shutdown | 74 |
| TOTAL | | $5890 |
| Additional Costs | | 175 |
| TOTAL | | $6065 |

### 2. Estimated System Costs

Cost of 1st unit (1979 dollars)........................$6065*

Cost of 100th unit (1979 dollars)......................$4390*

Cost of 1000th unit (1979 dollars).....................$2508*

Cost of 1000th unit (1977 dollars)
including overhead and profit........................$2867

Dollars per pound for 1000th unit (1977 dollars)........$4.59/pound

*Cost does not include overhead and profit.

### 3. Estimated Turnkey Costs

1977 dollars

Wind machine (1000th machine)..........................$2867

Tower (40 ft. Rohn 45 GSR).............................$ 700

Installation costs.....................................$1200
(assumes local labor & relatively accessible site; includes concrete, site preparation & labor)

Batteries..............................................$2000

TOTAL TURNKEY COST..................................... $6767**

**Turnkey costs can be as much as 100% higher depending upon site accessibility, storage requirements and required auxiliary generated facilities.

## 4. Cost of Energy Calculation

Base Data:

| | | | |
|---|---|---|---|
| IC | = Initial installed cost (turnkey) | = | \$6767.00 |
| FCR | = Fixed Charge Rate (commercial) | = | 0.085 |
| AOM | = Annual Operation & Maintenance Cost | = | 135.00 |
| AKWH | = Annual Kilowatt Hours produced (assumes 15 mph mean wind) | = | 7800 kilowatt hours |

For purposes of comparison with other DOE-funded prototypes, the cost of energy (COE) is calculated using the following formula specified by Rockwell:

$$COE = \frac{(IC)\ (FCR)\ +\ (AOM)}{(AKWH)}$$

$$COE = \frac{6767\ (0.085)\ +\ 135}{7800}$$

$$COE = \$.091 = 9¢ \text{ kilowatt hour}$$

# 10.0 UPDATED RELIABILITY ANALYSIS

All modifications that were made to the HR2 during Phase II are within the scope of reliability data developed in Phase I. The calculated mean time between failures (MTBF) for this machine is fifteen (15) years. Figure 10 is a reliability chart of the major systems showing subassembly reliability, major system reliability, and total reliability.

Assumptions used in generating Figure 10 are outlined below:

a. Reliability figures assume that the maintenance schedule is adhered to.

b. Slip rings, brushes and blades are replaced and/or refinished as necessary.

c. All non-moving structural parts (i.e., bolts, laminations, and fixed castings) are assigned a minimum lambda of .001 failures/million hours.

d. All moving components subject to failure and wear are assigned a minimum lambda of .07 failures/$10^6$ hours (except where contrary data are available).

e. Calculations of bearing failure rates are adjusted for the low rotational speeds of the rotor shaft, VARCS shaft and yaw column.

f. Component lambdas are corrected for estimated real cycles per hour.

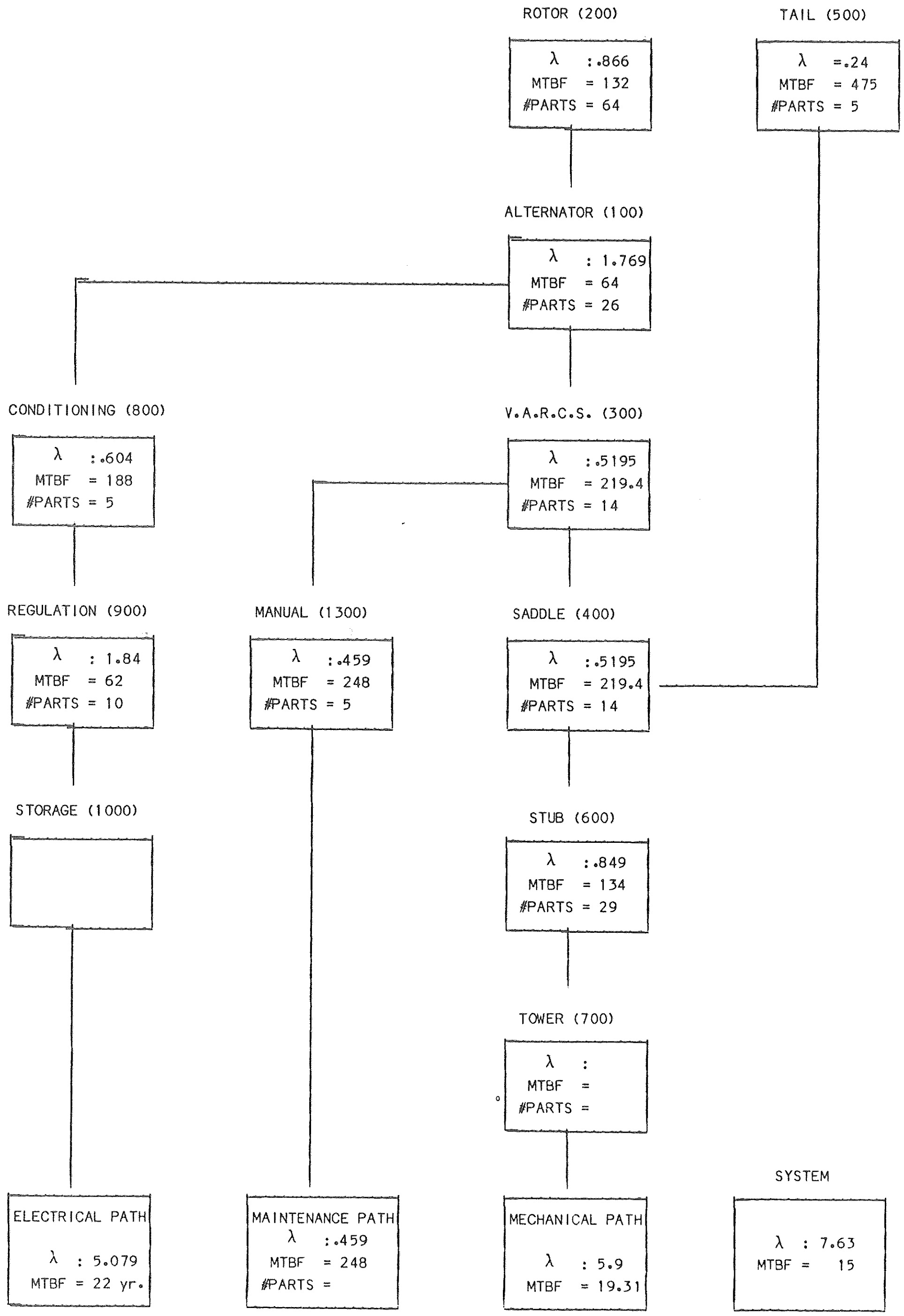



Figure 10

HR2 Reliability Flow Chart

## 11.0 MAINTENANCE PROCEDURES

The following is the routine maintenance procedure which should be conducted on the HR2 wind system at least once within any 365 day period to assure proper operation and long life of the SWECS. No preliminary maintenance is required at time of installation.

Annual Maintenance Procedures

1) Observe operating machine in wind in excess of 4 m/s (9 mph). Look and listen for any irregular operation, e.g.:

   a. Erratic pitch or yaw motion
   b. Rotor or system vibration
   c. Tower vibration
   d. Power output significantly reduced
   e. Unusual noise

2) Crank machine into service position (90 degree pitch-back).

3) Inspect and tighten, as necessary, all mechanical fasteners. (See Installation Section of Maintenance Manual for bolt torques.)

4) Check blade surfaces for cracks, breakage, erosion.

5) Inspect all brushes and slip rings for wear. Replace brush sets if there is less than 1/2 inch remaining. Be careful not to lose the spring from the inside of the housing during inspection.

6) All bearings are lubricated with Shell "Aeroshell" 7 at the time of manufacture. Bearings should only be lubricated with Aeroshell 7 or compatible equivalent. Grease fitting locations are 1) at the top of the stub tower, 2) on the front face of the alternator at the shaft, 3) at the rear of the alternator shaft, accessible by removing the diode cover.

7) Return machine to operating mode slowly.

## 12.0 CONCLUSIONS

Contractor testing of the prototypes has been completed. This program has been successful in meeting the goals of developing a product suitable for commercialization in the intended applications. Fabrication of the first prototype indicated a number of design changes which were immediately implemented in all three prototypes. Through the program of parallel testing by North Wind and Rocky Flats, running time was nearly doubled and the overall testing and redesign process accelerated.

Based on the HR2 test experience, North Wind has a high degree of confidence in the components and systems of the high reliability wind system. The present configuration of the commercial HR2 is representative of the critical design area modifications that were made as a result of both Rocky Flats and North Wind Power Company free-stream test programs.

## 13.0 REFERENCES


1. North Wind Power Company 2 Kilowatt High Reliability Wind System, Phase I - Design and Analysis, July 1981, D. J. Mayer and J. H. Norton, Jr., North Wind Power Company, Inc., (RFP-3310/2).

2. North Wind Eagle 3 Wind Turbine Generator, Final Test Report, January 1980, J. H. Sexton, Rocky Flats Wind Systems Program, (RFP-3071).

# APPENDIX A

## Drawing Revisions

DRAWING NUMBER: 2K000

DRAWING DESCRIPTION: Master Drawing

REVISIONS: Delete front vent
Delete Pyle-National Connector
Add power cable boot
Simplify power conduit
Simplify VARCS spring hub
Redraw VARCS bearings as spherical roller type
Change VARCS centerline to rotor hub distance to reflect final endbell dimensions
Change diode mounting lock detail
Delete O-ring seals
Change VARCS Disc dimension to reflect final design
R1-Add centerline offset at saddle

DRAWING NUMBER: 2K100

DRAWING DESCRIPTION: Alternator (Exploded View)

REVISIONS:
R1-Bearing seal fasteners decreased to 1/4-20NC
R2-Delete O-ring seals
Add #406 woodruff key for sliprings
Delete front labyrinth seal retaining ring

DRAWING NUMBER: 2K111

DRAWING DESCRIPTION: Stator Laminations

REVISIONS:
R1-Add material specification

DRAWING NUMBER: 2K120

DRAWING DESCRIPTION: Lundels; Alternator Shaft

REVISIONS:
R1-Rear bearing retainer ring seat added to shaft
R2-Shaft dimensions recalculated and corrected
R3-Corrected shaft taper angle as drawn
R4-Deleted front retaining ring seat at rear bearing
R5-Bore depth shortened on Lundel to allow .125" magnetic washer

DRAWING NUMBER: 2K130

DRAWING DESCRIPTION: Alternator Endbells

REVISIONS:
- R1-Keyseat deleted
- R2-Front bearing seal mounting fastener holes reduced to 1/4-20NC
- R3-Drawing changed to reflect ribbing detail

DRAWING NUMBER: 2K200

DRAWING DESCRIPTION: Rotor (Exploded View)

REVISIONS:
- R1-Transverse blade bolts 3/8-16NC
- R2-Hardware numeration updated

DRAWING NUMBER: 2K220

DRAWING DESCRIPTION: Rotor Hub Casting

REVISIONS:
- R1-Drawing changed to reflect new pattern work at nose cone rim
- R2-Increase nose cone fasteners to 1/4-20NC
- R3-Change nose cone fastener bolt circle diameter for production nose cone

DRAWING NUMBER: 2K230

DRAWING DESCRIPTION: Nose Cone

REVISIONS:
- R1-Holes relocated for production rotor hub
- R2-Dimensions changed for production rotor hub

DRAWING NUMBER: 2K240

DRAWING DESCRIPTION: Rotor Hub Plate

REVISIONS:
- R1-Change flange direction 180° to correct drafting error

DRAWING NUMBER: 2K300

DRAWING DESCRIPTION: VARCS (Exploded View)

REVISIONS: Simplify power conduit
Simplify VARCS spring hub
Redraw VARCS bearings as spherical roller type
R1-Decrease power connector flange fasteners to 1/4-20NC
R2-Increase spring bracket bolts to 1/2-13NC

DRAWING NUMBER: 2K310

DRAWING DESCRIPTION: Alternator Support Casting

REVISIONS:
R1-Delete VARCS bearing retainer ring seats
R2-Relocate grease fittings
R3-Add hole for Common connection
R4-Add cover holes

DRAWING NUMBER: 2K320

DRAWING DESCRIPTION: VARCS Shaft, Hub; Top Tower Plate

REVISIONS:
R1-Add Top Tower Plate
Revise VARCS hub
R2-Revise VARCS shaft for simplified VARCS hub
R3-Revise VARCS bearing seat dimensions
R4-Rotate VARCS bolt hole through VARCS shaft 30°

DRAWING NUMBER: 2K331

DRAWING DESCRIPTION: VARCS Spring

REVISIONS: Increase spring rate to 71 in-lb/degree
R1-Revise hole locations and effective spring length

DRAWING NUMBER: 2K333

DRAWING DESCRIPTION: VARCS Disc; Spring Bracket

REVISIONS: Revise VARCS disc interface with ASC
R1-Correct spring bracket material to ASTM 148-73
R2-Revise spring bracket dimensions for 3/4" cam followers
R3-Revise VARCS disc internal dimensions

DRAWING NUMBER: 2K335

DRAWING DESCRIPTION: VARCS Cover

REVISIONS: Add 5° draft to OD
R1-Add 1" depth for new spring bracket and stop assembly

DRAWING NUMBER: 2K400, 500, 600

DRAWING DESCRIPTION: Stub Tower (Exploded View)

REVISIONS: Revise centerline offset and saddle ears
R1-Add slipring assembly key
R2-Add brushholder part numbers

DRAWING NUMBER: 2K420

DRAWING DESCRIPTION: Saddle

REVISIONS:
R1-Add longitudinal section
R2-Rotate VARCS shaft seat
R3-Change centerline offset and casting configuration
R4-Revise bearing seat dimensions and tail bolt holes

DRAWING NUMBER: 2K500

DRAWING DESCRIPTION: Tail Assembly

REVISIONS: Lengthen tail support arms

DRAWING NUMBER: 2K510

DRAWING DESCRIPTION: Tail Vane

REVISIONS: New Drawing

DRAWING NUMBER: 2K640

DRAWING DESCRIPTION: Tower Plate

REVISIONS:
R1-Add slipring cover mounting holes
R2-Tighten tower tube inset dimensions
R3-Revise cover hole dimensions

DRAWING NUMBER: 2K660

DRAWING DESCRIPTION: Power Brush Assembly Cover

REVISIONS: New Drawing

DRAWING NUMBER: 2K900

DRAWING DESCRIPTION: Field Regulator

REVISIONS: New Drawing